"Assisted Research and Analysis of the Wave Phenomena and the Associated Pulse Periods Due to Cavitating Bubbles"

by

Charles Schornak
Mechanical Engineering
Fluid Theory Concepts 490

Partial Fulfillment of ME 490, approved by F G Hammitt

Financial Support Provided by: Office of Naval Research Contract No NOOO14-76-C-0697

June 28, 1977
Contents

Abstract 3
Purpose 5
Introduction 4
Discussion 8
Concluding Remarks 11
Film Analysis 13
Calculations 15
Graphs 17
Photographs 25
Bibliography 29
Abstract

This report contains information on the characteristics of bubble collapse, especially the periods of oscillations and some aspects of bubble dynamics. A general definition of cavitation is presented so as not to exclude artificially produced phenomena of the same nature but occurring under different circumstances. Cavitation is understood as a phenomenon of its own and not merely as some kind of nonlinearity. Some further thoughts are presented in the future development of basic cavitation research.

Purpose

As in the past, similar reports of this nature have been documented for the purpose of recording experimental findings and assisting in continued research.
Introduction: General and Basic Aspects of Cavitation

A general description of cavitation may consist of the study and research of the occurrence of cavities in matter under special circumstances. Cavitation is a group of phenomena which are associated with the occurrence of cavities in a liquid, especially their formation, motion, and the physical, chemical, and biological effects thereby produced. A cavity in a liquid (often called a cavitation bubble) is any bounded volume of space being empty or containing vapor and/or gas with a defined physical boundary at least part of which must be made up of liquid.

Some special cases involve the cavity in a liquid obtained by pressure reductions in flowing systems or by the underpressure in sound fields. In the first case cavitation is the result of a localized pressure reduction in a flowing system. It is characterized by the formation of vapor bubbles in a localized region sustaining a pressure below the vapor pressure of the fluid at the local temperature and pressure.

Cavitation is introduced in this definition as a group of phenomena. The definition contains implicitly that cavitation is not simply a nonlinear phenomenon of some kind but is a phenomenon of its own. The notion of this will greatly influence the manner of attacking problems and
may also be used as a guideline where the usual nonlinear approaches may fail in describing the phenomena observed.

Thus are the two main areas of research: hydraulic cavitation and acoustic cavitation. Hydraulic cavitation is associated with all kinds of hydraulic systems: for example, ship propellers, turbine blades, hydrofoils, and pumps. The occurrence of cavitation lowers the efficiency, often leads to a quick deterioration of the parts being exposed to cavitation, and can be the source of intense noise radiated into the liquid. Acoustic cavitation appears in sound fields at sufficiently high sound pressure amplitudes. It is unwanted in underwater acoustics where signals are to be transmitted over a long range, and in ultrasonic diagnostics, where, for example, the interior of the human body is scanned with the aid of sound waves. In industry, acoustic cavitation has found some application in cleaning, complex parts, in emulsification, and deintegration.

To do research work on cavitation, a few standard facilities have been developed. In hydraulic cavitation, most research work has been done using cavitation tunnels, as they are called. These facilities are capable of producing a flow of liquid with adjustable parameters such as flow velocity, pressure in the liquid, gas content of the liquid and so on. A schematic of this equipment is shown in diagrams 1 and 2.
Dia. 2. The Plexi-glass 3/4 in. Diameter Venturi Test Section
aid of a pump a liquid flow is generated through a test section whose cavitation on submerged bodies can be studied.

An acoustic cavitation is a variety of direct test. An example of one such device is shown in diagram 3. The device is mainly used for cavitation erosion tests. The probe to be tested forms the top of an amplitude transformer dipped in the liquid and driven by a transducer on the other end. The transducer is usually made up of a series of nickel plates (using magnetostriction) or a cylinder of piezoelectric material like BaTiO₃ or PZT ceramics. The probe is sometimes put at some distance opposite to the top of the amplitude transformer to eliminate the large accelerations encountered during the vibration of the transformer.

Cavitation damage and noise can be said to be the most important cavitation phenomena. We now know a lot about this phenomena, but we are far from being sure about the details. However, to understand the action of cavitation, the dynamics of the produced cavitation bubbles or cavitation bubble fields must be looked at. Thus cavitation bubble dynamics is the fundamental area of research in cavitation. Explanation of observed phenomena can only be expected with bubble dynamics as a basis. But theoretical studies as well as experiments in this field of cavitation research are difficult because of the many parameters and aspects involved which cannot be
Vibratory Facility Cavitation Erosion Study In Sodium.

Dia. 3
suitably taken into account (like nonspherical bubbles) or controlled (like the formation of spherical bubbles in experiments). The first step in attacking the problem has of course been to put aside the real cavitation bubble fields and to start with models of single cavitation bubbles looking at their properties and comparing them with known phenomena.

The R.N.N.P. (Rayleigh - Nettleship - Nippiras - Pritchard) bubble model is a nonlinear differential equation which includes the effects of gas content, surface tension, and viscosity. The differential equation is of the form

\[ \dddot{R} + \frac{3}{2} \frac{\dot{R}}{R} \dot{R}^2 = \frac{1}{\rho R} \left[ \rho_n (\frac{R}{R})^{3k} + P_0 - \frac{2\sigma}{R} - P_s - \frac{4\mu}{R} \dot{R} + \dot{P}(t) \right] \]

where \[ P_n = \frac{2\sigma}{R} + P_s - P_0 \]

It is not known what value might be inserted for \( k \) as almost nothing is known about the gas content inside the bubble. It may lie between 1.00 and 1.67 and may alter during bubble oscillation. The curve shown in the diagram below was calculated for a constant intermediate value (\( k = 1.33 \)). The R.N.N.P. model seems to give an appropriate description of the bubble investigated.
Discussion

Several high-speed films have been analyzed along with previously recorded data on bubble oscillations and the results were recorded as graphs in the following figures.

In figures 1 and 2, the maximum period of oscillation for a given number of occurrences is depicted. The system parameters are as follows: system pressure 4 psi, ventur inlet pressure 17 psi, ventur outlet pressure 12 psi, water temperature 62°F, and the manometer read 3 in. Hg. Likewise, in figures 3 and 4, the maximum period of oscillation for a given number of occurrences is represented. The system parameters are as follows: system pressure 1 atm, ventur inlet pressure 7.5 psi, ventur outlet pressure = 0 psi, water temperature 60°F, and a manometer reading of 42 in. Hg.

For the figures 5 and 6, the maximum period of oscillation for a given number of occurrences is shown where the data was obtained from a static spark in a spark generator. Point number 1 represents the first period having a maximum amplitude, and period number 2 corresponds to the second period (rebound) and second maximum amplitude.

The graphs were obtained by recording the average period of bubble oscillation for a given number of occurrences. This entails analysis of photographic pictures of bubble oscillations as recorded...
on film from an oscilloscope. Events of bubble oscillation were detected by use of two pressure sensitive probes (the U.M. probe and the Kestle probe). The signal produced by the probes was then monitored on an oscilloscope. Shown in the pictures below are examples of these bubble oscillations as recorded from a flowing system as in the case of the venturi tunnel and as in a static system of a spark generator.

VENTURI OUTPUT PULSE 50 μsec/div

SPARK GENERATOR PULSE 1 ms sec/div
High speed film analysis enabled the discovery of bubble behavior once the film speed was secured. Calculation of bubble collapse and its corresponding period was possible by analysis of individual frames. The results are tabulated on pages end of this report.

It is interesting to note the result of combining the graphs in figures 1, 2, 3, 4, 5 and 6. The graph of figure 7 depicts this result. The graph shares much similarity with the behavior of the R. N. N. P. bubble model theory.
Concluding Remarks

Both aluminum and glass represent extreme material behavior. They have not been in use for long as parts of a machine which have been damaged by implosive bubbles. It is very useful to study the behavior and the different stages of damage of model materials when subjected to implosive cavitation bubbles.

Of special interest in bubble dynamics is the final stage of bubble collapse. Due to the sufficiently good repeatability of bubble size, bubble collapse could be filmed with picture repetition rates of 5000 f.p.s. (refer to figure 3). The pictures taken confirm that bubble collapse in its final stages is an extremely fast event. In the case shown the jet formation is evident. Jet speed can be estimated to lie between 100 m/sec and 200 m/sec.

When extrapolating results from one material to another, we must not only look at the structures, which surely have an influence on the behavior of the material under this special loading, but also the change in mechanical properties. This is of great importance especially if we want to find out something about the cavitation resistance of heterogeneous materials with their different mechanical properties in particular phases.

These particular phases often differ very much in their cavitation resistance. It is not sufficient to know only the
resistance of each single phase to predict the cavitation-resistance of the whole material, because of the change in the surface of each phase may have a great influence on the behavior of the other phases.

Differences in the shape of the damage caused by a single bubble implosion and a single liquid jet impact result from different test conditions. The cavitation test specimen will always be covered with a liquid layer, so that the jet, formed when the bubble implodes, cannot reach the surface directly. The liquid layer reduces the effect of the jet, and its thickness has an influence on the damage.

Possibilities in basic cavitation research are promising. There is neither a lack of ideas nor methods to go on (refer to figures 9 and 10). An interesting subject is illustrated here, captured by a movie camera having a film speed of 3000 fps. This phenomena is only desirable of future study in that the understanding of its behavior might be more than simply random coincidence.
### A.S.M.E. - Film Analysis

<table>
<thead>
<tr>
<th>No. Oscillations</th>
<th>Period No. 1</th>
<th>Period No. 2</th>
<th>Period No. 1</th>
<th>Period No. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(No. Frames)</td>
<td>(No. Frames)</td>
<td>(No. cm)</td>
<td>(No. cm)</td>
</tr>
<tr>
<td>Grow</td>
<td>Collapse</td>
<td>Grow</td>
<td>Collapse</td>
<td>Grow</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3+</td>
</tr>
<tr>
<td></td>
<td>1/5</td>
<td>3/8</td>
<td>3/8</td>
<td>2/15</td>
</tr>
<tr>
<td>Film Speed</td>
<td>8000 fps</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Charles Kline - Film Analysis

<table>
<thead>
<tr>
<th>No. Oscillations</th>
<th>Period No. 1</th>
<th>Period No. 2</th>
<th>Period No. 3</th>
<th>Period No. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(No. Frames)</td>
<td>(No. Frames)</td>
<td>(No. cm)</td>
<td>(No. cm)</td>
</tr>
<tr>
<td>Grow</td>
<td>Collapse</td>
<td>Grow</td>
<td>Collapse</td>
<td>Grow</td>
</tr>
<tr>
<td>4</td>
<td>?</td>
<td>50</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>8</td>
<td>8</td>
<td>8 (?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Period No. 1</th>
<th>Period No. 2</th>
<th>Period No. 3</th>
<th>Period No. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(No. cm)</td>
<td>(No. cm)</td>
<td>(No. cm)</td>
<td>(No. cm)</td>
</tr>
<tr>
<td>Grow</td>
<td>Collapse</td>
<td>Grow</td>
<td>Collapse</td>
</tr>
<tr>
<td>?</td>
<td>2</td>
<td>1/5</td>
<td>1/6</td>
</tr>
<tr>
<td>1/5</td>
<td>1/6</td>
<td>1/4</td>
<td>1/4</td>
</tr>
</tbody>
</table>

(16 fps x $1.57 \times 10^4$ time magnification = $2.512 \times 10^5$ fps)

**Note:** A period consists of a short rise time followed by a longer decay time.
A.S.M.E. Film Analysis (8000 fps)

<table>
<thead>
<tr>
<th>No. of Oscillations</th>
<th>Collapse Period (Frames)</th>
<th>Collapse Period (m.sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>1.000</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>1.125</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>0.750</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>0.750</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>1.000</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>0.625</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>0.750</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>0.750</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>0.625</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0.500</td>
</tr>
</tbody>
</table>

Film Analysis of Bubble Growth and Collapse in Water in a 2-Dimensional Venturi by R.D. Ivany (8000 fps)

<table>
<thead>
<tr>
<th>No. of Oscillations</th>
<th>Collapse Period (Frames)</th>
<th>Collapse Period (m.sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>0.500</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>0.875</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>0.875</td>
</tr>
</tbody>
</table>
Period No. 1

Grow: \( \sqrt{8000 \text{ fps} \times 2 \text{ frames}} = 0.250 \text{ m/sec} \)

Collapse: \( \sqrt{8000 \text{ fps} \times 1 \text{ frame}} = 0.125 \text{ m/sec} \)

Total: 0.375 m/sec

Period No. 2

Grow: \( \sqrt{8000 \text{ fps} \times 2 \text{ frames}} = 0.250 \text{ m/sec} \)

Collapse: \( \sqrt{8000 \text{ fps} \times 3 \text{ frames}} = 0.375 \text{ m/sec} \)

Total: 0.625 m/sec

The combination of the two periods is 1.000 m/sec and this represents the entire bubble life from inception to annihilation.

Charles Kline Film - Calculation

Period No. 1

Grow: \( \sqrt{2.512 \times 10^5 \text{ fps} \times ?} = \odot \)

Collapse: \( \sqrt{2.512 \times 10^5 \text{ fps} \times 50 \text{ frames}} = 0.199 \text{ m/sec} \)

Total: 0.199 m/sec

Period No. 2

Grow: \( \sqrt{2.512 \times 10^5 \text{ fps} \times 25 \text{ frames}} = 0.0995 \text{ m/sec} \)

Collapse: \( \sqrt{2.512 \times 10^5 \text{ fps} \times 20 \text{ frames}} = 0.0796 \text{ m/sec} \)

Total: 0.179 m/sec
**Period No. 3**

Grow: \( \frac{1}{2.512 \times 10^5 \text{ fps}} \times 12 \text{ frames} = 0.0478 \text{ msec} \)

Collapse: \( \frac{1}{2.512 \times 10^5 \text{ fps}} \times 8 \text{ frames} = 0.0312 \text{ msec} \)

Total: \( 0.0796 \text{ msec} \)

**Period No. 4**

Grow: \( \frac{1}{2.512 \times 10^5 \text{ fps}} \times 8 \text{ frames} = 0.0318 \text{ msec} \)

Collapse: \( \frac{1}{2.512 \times 10^5 \text{ fps}} \times 12 \text{ frames} = 0.0478 \text{ msec} \)

Total: \( 0.0796 \text{ msec} \)

The combination of the four periods is \( 0.5372 \text{ msec} \) and this is not representative of the total bubble life since the inception of the bubble was not observed.
Figure 4.
Spark Generator - Period No. 1

No. OF Occurrences

\( \lambda \) (m. sec)

Figure 5
Figure 8. Dynamics of a spherical cavitation bubble in water in the vicinity of a plane solid boundary after collapse. The pulse repetition rate is 2,000 Hz.
Figure 9, and 10, exhibits two bilateral, non-spherical, cavitation bubbles.
Bibliography


2. R is the radius of the spherical bubble, p the density of the liquid, R_n the radius of the bubble at rest, P_n the gas pressure inside the bubble for R = R_n, K = C_p/C_v the ratio of the specific heats inside the bubble, P_s the vapor pressure of the liquid, σ the surface tension of the liquid, P_h the hydrostatic pressure at the location of the bubble, η the viscosity of the liquid, and P(t) an arbitrary time varying pressure.